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Improving the integrated hybrid LCA in the upstream scope 3 emissions inventory analysis

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Abstract
Purpose The protocols of carbon footprints generally define three scopes for different greenhouse gas (GHG) emissions levels. The most important carbon footprint emissions source comes from upstream indirect emissions of scope 3 for products that do not consume energy during their use phase. Upstream scope 3 GHG inventory can usually be analyzed through input–output or hybrid LCA analysis. The economic input–output life cycle analysis (EIO-LCA) and the hybrid LCA model have been widely used for this purpose. However, a cutoff error exists in the hybrid model, and the lack of a truncation criterion between process and IO inventory may lead to a high level of uncertainty in the hybrid model. This study attempts to improve the problem of cutoff uncertainty in hybrid LCA and proposes a method to minimize the cutoff uncertainty.
Methods The way to improve the cutoff uncertainty could follow two steps. First, through the IO inventory analysis of EIO-LCA, we can define the emissions by various tiers of product components. The IO inventory indicator can provide a definitive criterion for the process inventory of the hybrid model. Second, we connect the process- and IO-LCI according to the IO inventory result. The advantage of the process inventory is that it provides detailed manufacturing information on the target while the IO encompasses a complete system boundary. For improvements, the process inventory can catch the most important process of the GHG emissions, and the IO inventory could compensate for the remainder of the incomplete system inventory.
Results and discussion In this case study, the printed circuit board production process is used to evaluate the efficiency of the improved method. The threshold *M* was set to 70 in this case study, and the IO inventory provides the remaining 30 %. For the integrated hybrid model, the tier 3 process inventory takes only 64 % while the incorporation of the proposed method can include 92 % of the total emissions, which shows the cutoff uncertainty can be reduced through the improvement.
Conclusions This study provides a clear guideline for process and IO cutoff criteria, which can help the truncation uncertainty. When higher precision is required, process LCI will need to play an important role, and thus, a higher *M* value should be set. In this situation, the emissions from IO-LCI would be smaller than the emissions from the process LCI. The appropriate solution would attain a comfortable balance between data accuracy and time and labor consumption.

Keywords Carbon footprint · EIO-LCA · Integrated hybrid LCA · LCA uncertainty · Print circuit board · Scope 3

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1 Introduction

1.1 The overview of emission in upstream scope 3

Hybrid life cycle assessment (hybrid LCA) is an effective model for evaluating product greenhouse gas (GHG) emissions for the whole supply chain. However, uncertainty is an important issue when a hybrid model is used. The purpose of the paper is to deal with one of the uncertainties faced by hybrid LCA used for GHG inventory analysis. For an

enterprise, the carbon footprint (CFP) inventory is the first step to reducing GHG emissions. Because of the high level of concern regarding the global warming issue, product suppliers and manufacturers have a strong motivation to reveal GHG emissions for the product itself and for the upstream supply chain. The whole product life cycle GHG emissions from the raw material excavation stage through the end-of-life stage are called the product carbon footprint (Sinden 2009).

LCA is the appropriate method to calculate product CFP, which includes the GHG emissions from raw material excavation, manufacture, and transportation, to consumer use and end-of-life treatment. To separately account for direct and indirect emissions, various GHG protocols categorize direct and indirect emissions into scopes. The emissions of scope 1 include the GHG onsite direct emissions. The scope 2 includes the indirect GHG emissions from the consumption of purchased electricity, heat, or steam. Other indirect emissions are attributed to scope 3, the most difficult part of the inventory, such as the production of a purchased component, materials, and fuels, which are not owned or controlled by the reporting entity. All indirect emissions that occur in the company supply chain included both upstream and downstream emissions (WRI and WBCSD 2011). This study focuses on upstream scope 3 emissions, since it is typically most important for products that do not consume energy during use phase.

Because of the difficulty of upstream scope 3 inventory analysis in time and labor consumption, the traditional LCA usually uses a commercial database, such as Ecoinvent. However, more than 75 % of the GHG emissions arise in scope 3 (Huang et al. 2009), which means that most GHG emissions come from the upstream supply chain but rely on an inventory database that has the potential of high uncertainty. Different inventory databases could lead to diverse results because of inappropriate system boundary definitions and incomplete data quality (Andrae and Andersen 2010). As we know, the deeper the inventory analysis we conduct, the more complete the system we have. As a case study, Lenzen's analysis of the Australian commodity groups shows that an inventory analysis to tier 10 is needed to achieve 90 % system completeness (Lenzen 2000). Despite the fact that the upstream supply chain is the main source of the product's GHG emissions in many cases, the labor and time consumption are the major constraints of the upstream inventory analysis.

1.2 Life cycle analysis in upstream scope 3 inventory

The purpose of LCA is to quantify the input and output during all of the life stages of a product, including raw materials, fuel, main products, supplementary products, and waste emissions. Top-down and bottom-up are the main approaches used in obtaining GHG emissions inventory. The top-down approach data have been periodically available in national statistics, and input–output (IO) analysis (IOA) has been used to extend the boundaries of the product system boundary in LCA. The bottom-up approach, process LCA, utilizes high-resolution detailed site-specific data. Compared to the process LCA approach, the methodology based on the IO model could include wider system boundaries of the entire economy (Hendrickson et al. 1998).

IO-LCA has continually been developed since the 1990s and was based on the IO table of economic activity (Lave et al. 1995; Hendrickson et al. 1998). IO-LCA is another solution for the incomplete system boundaries and indirect effects in process LCA. With its ease of rapid analysis on the overall resources input and environmental impact of the supply chain, the IO-LCA model has rapidly grown in popularity and has become indispensable (Suh and Kagawa 2005). However, IO-LCA has limitations, e.g., the varying prices of products in the same sector, the temporal nature of the data, and the aggregation of the IO table by coincidence assumptions of technique coefficients; these limitations could distort the LCA result.

It is because the process- and IO-LCA provide complementary advantages that hybrid LCA integrates both together and has become a popular inventory analysis method over the past decade. The term "hybrid" has two meanings; one meaning is to combine the use of both physical and monetary units, and the other meaning is to integrate IO and process data (Suh et al. 2003). There are four steps for constructing a hybrid model (Treloar et al. 2000): (1) derive an input–output LCA model, (2) extract the most important pathways for the evaluated sector, (3) derive specific data for the evaluated product and components, and (4) substitute the case-specific LCA data into the input–output model. As the hybrid model integrates IO and process data, the inventory becomes more complete than before. In general, the hybrid LCA model has five types of uncertainty: data inventory, system cutoff error, IO table aggregation, and temporal and geographic uncertainty (Williams et al. 2009). Data uncertainty occurs in inputs with inadequate parameters or data. Cutoff error arises when the definition of the system boundary has inconsistency or there is truncation error between the process and the IO inventory. Aggregation uncertainty arises in the sector attribute of an inadequate group. The misfit of geographic and temporal scales could also lead to uncertainty in the hybrid model.

1.3 Hybrid model limitation and the purpose of this study

Hybrid approaches can be categorized into three groups: the tiered hybrid model, the input–output-based hybrid model, and the integrated hybrid model (Suh et al. 2003). Integrated hybrid analysis was proposed by Suh (2004) and Suh and

Huppes (2005), and the process data are represented as a matrix by physical units that combine with input–output tables using monetary units. Compared to two other hybrid models, the integrated model is consistent in its mathematical framework and could avoid double counting. However, the truncation between the IO and process data needs a clearer definition, since the connection of the monetary IO table with different tiers of process inventory levels results in a variety of consequences. For example, the hybrid model of the monetary IO table connects to the process matrix between tier 1 and tier 5 can lead to a considerable difference. With a higher tier of the process inventory level, the uncertainty would be lower, which implies a higher time and labor demand. Thus, the dilemma between the efforts spent on inventory analysis and the assessment uncertainty must be resolved as appropriate the goals of the assessment. Structural path analysis (SPA) is an excellent method to rank the IO analysis significant emission and has been used with LCA (Treloar 1997). SPA can extract and rank significant paths in input–output-based techniques (Lenzen 2007). It has also been conceptualized into a new hybrid approach, Path eXChange method (PXC), to facilitate meaningful inclusion of detailed process data at lower labor and data cost (Lenzen and Crawford 2009; Baboulet and Lenzen 2010).

Compared to IO-LCA, the hybrid model is much more appropriate for calculating the detailed product carbon footprint. As mentioned above, an inappropriate system boundary could lead to truncation error. For a tiered hybrid model, system incompleteness factors were proposed to avoid double counting and to minimize the truncation error (Rowley et al. 2009). In an integrated hybrid model, the truncation error exists between the junction of the IO and the process matrix. This research addresses the truncation error problem in the integrated hybrid model. In this, the author proposes a compromise route to improve the truncation uncertainty for the integrated hybrid model. In the end, the print circuit board as a case study demonstrates the utility of the proposed method.

2 Materials and methods to improve the integrated hybrid model

The main goal of this improvement is to minimize the truncation uncertainty and to develop criteria for truncation between the process and IO inventories. For the hybrid model, the detailed inventory data should be gathered by the process LCI rather than the IO-LCI. However, the abovementioned process inventory will exhaust most of the time and labor resources. Under the limitations of resources, dividing the contribution between the process and IO inventories has become an important issue. This study developed a cutoff criterion in two steps as follows:

Step 1 IO inventory through EIO-LCA

For the integrated hybrid model, each process element can match one IO sector. Different sectors have different emissions characteristics. Take the electricity sector in Taiwan for example; over 50 % of the energy comes from thermal power, and the GHG emissions are mostly attributed to the tier 1 supply chain. In contrast, for the services sector, the GHG emissions at a higher tier play a more important role than at a lower tier. The emissions of a sector can be estimated through IO analysis.

The economic input–output (EIO)-LCA model can be expressed as a power series, as shown in Eq. (1); this equation can represent the production output at a different tier. Ri represents the emissions per dollar of output for each sector. The output contribution by the desired product itself is ($I\times y$); the first tier supply chain is ($A\times y$), and the second tier of indirect suppliers is ($A\times A\times y$), where A is the direct requirement matrix and y is the output (Matthews et al. 2008).

$$(I-A)^{-1}=\left(I+A+A^2+\ldots\ldots.A^{\infty}\right)Y \qquad (1)$$

$$\text{Up to tier 1}:\ \mathrm{bi}=\mathrm{Ri}(I)y=\mathrm{Ri}y \qquad (2)$$

$$\text{Up to tier 2}:\ \mathrm{bi}=\mathrm{Ri}(I+A)y \qquad (3)$$

$$\text{Up to tier } n:\ \mathrm{bi}=\mathrm{Ri}(I+A+A2+\ldots An-1)y \qquad (4)$$

Based on Eqs. (1), (2), (3), and (4), the emissions of contributions from different tiers in sector i could be known. For the hybrid model, each process element of the product corresponds with one sector, according to the characteristics of the component. The results are helpful for defining how many tiers should be in the inventory of the process element. We can determine the emissions of the process inventory value $K_i^n\%$, where n is the tier of the supply chain and the values of i are the sectors. The remaining part of the emissions inventory, $\left(1-K_i^n\right)\%$, can be the IO inventory. Through the IO inventory by the IO model, the bonding of the process and IO in the integrated hybrid model could be at tiers 1, 2, or n. The higher value of $K_i^n\%$, the higher the tier of the supply chain that should be inventoried and the higher the data reliability. The IO inventory indicator ensures the inclusion of important emissions sources in the process inventory. The process inventory discussed in this paper is primary data because in some cases secondary process inventory data available from a database may be inferior to the IO inventory data.

Step 2 Connect the process and IO-LCI according to the IO inventory result

The difference between the integrated hybrid model and the other two hybrid models is the IO table interconnected with the physical system, in one matrix. The integrated hybrid model can be expressed as Eq. (5) (Suh 2004, 2006; Suh and Huppes 2005)

$$M_{IH} = \begin{bmatrix} \widetilde{B} & 0 \\ 0 & B \end{bmatrix} \begin{bmatrix} \widetilde{A} & Y \\ X & I - A \end{bmatrix}^{-1} \begin{bmatrix} \widetilde{k} \\ 0 \end{bmatrix} \tag{5}$$

M_{IH} Total supply chain emissions
$\widetilde{B}$ The emissions of the process
B The emissions of the IO
$\widetilde{A}$ Process-based matrix
X Upstream cutoff flows to the LCA system, representing a unit of monetary value per operation
Y Downstream cutoff flows to the IO system, representing a unit of physical unit per monetary
I Identity matrix
A Technical coefficients
$\widetilde{k}$ External demand output

For Eq. (5), $\widetilde{A}$ is the most important source for the truncation error. The $\widetilde{A}$ matrix can be either a one-tier matrix with a higher uncertainty or a high-tier matrix with a higher level of precision. The IO inventory indicator can provide a definitive criterion for the inventory. We can determine that the process inventory should be more than $M\%$. Thus, the appropriate inventory tier is n when $K_i^n M\%$.

Figure 1 shows the improvement from the truncation rule. Figure 1a is the normal hybrid model, and Fig. 1b is the improved model. Suppose that the product we evaluate needs four major steps, and that each step obtains its own components in various tiers. In the tier 1 supply chain, there are six different components ((a), (b), (f), (k), (n), (r)), and each component belongs to a sector (A, E, B, C) according to the categories of the characteristics. As shown in Fig. 1, sector A meets threshold ($M\%$) in tier 1, and the components (a) and (n) conjoin the IO table in tier 1. In the same way, sector F meets threshold ($M\%$) in tier 2; thus, the component (f) conjoins the IO table in tier 2.

3 Print circuit board case study

3.1 Case study result

This study took printed circuit board GHG emissions as an example. The data were extracted from the Ecoinvent

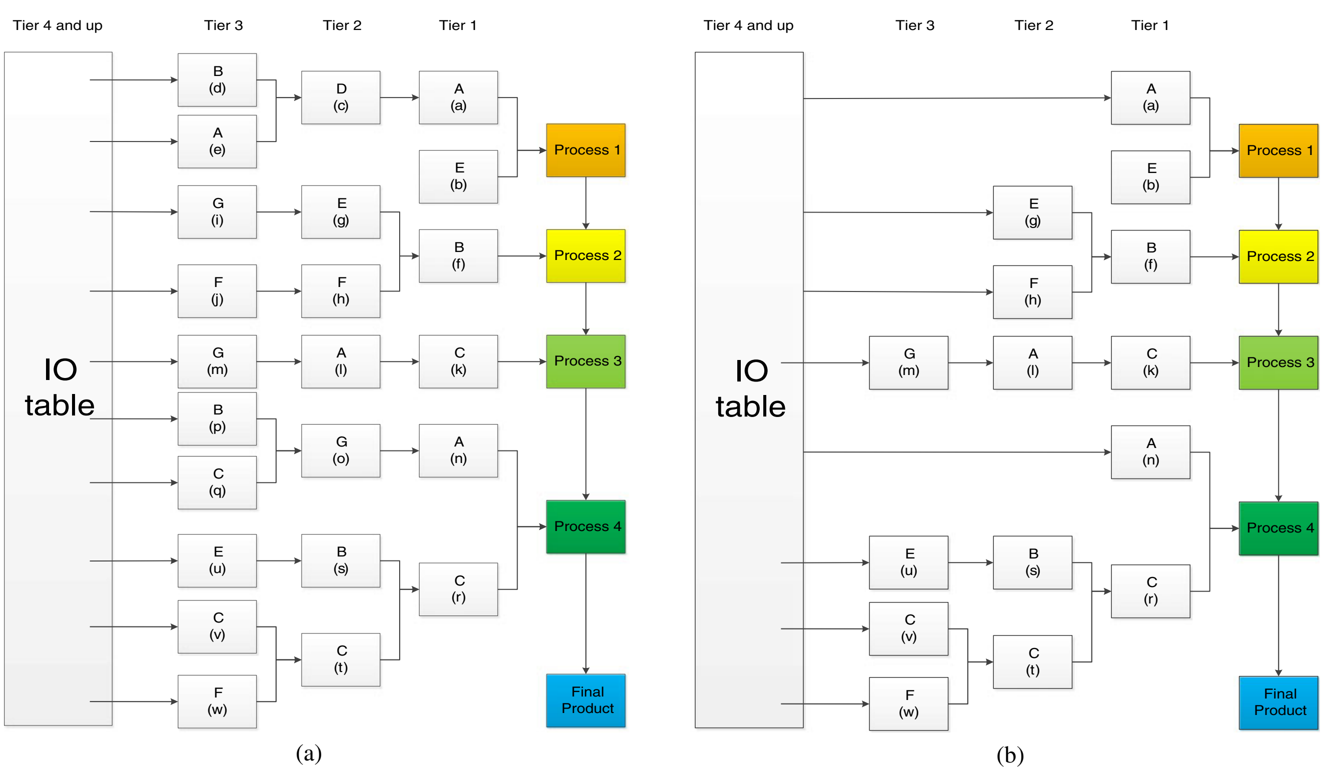

Fig. 1 The improvement of cutoff rule from a traditional hybrid LCA (**a**) to the proposed inventory system (**b**)

Table 1 IO inventory result of the printed circuit board, 16 components

Tier 1 component	Match sector[a]	Tier 1 emission (%)	Tier 2 emission (%)	Tier 3 emission (%)	Tier 4 emission (%)	Inventory depth
Copper	23	12.22	58.82	82.52	92.57	4
Dipropylene glycol monomethyl ether	16	51.99	79.60	91.71	96.67	3
Glass fiber-reinforced plastic	20	2.09	52.18	79.44	91.51	4
Hydrochloric acid	16	51.99	79.60	91.71	96.67	3
Hydrogen peroxide	16	51.99	79.60	91.71	96.67	3
Iron(III) chloride	22	44.48	73.97	88.56	95.07	3
Nickel	23	12.22	58.82	82.52	92.57	4
Phenolic resin	20	2.09	52.18	79.44	91.51	4
Sheet rolling	24	2.69	46.90	75.61	89.38	4
Sodium chloride	06	15.14	47.67	71.22	85.43	4
Sodium hydroxide	16	51.99	79.60	91.71	96.67	3
Sulfuric acid	16	51.99	79.60	91.71	96.67	3
Tin	23	12.22	58.82	82.52	92.57	4
Natural gas	34	1.50	55.27	88.15	96.25	4
Tap water	35	0.45	57.42	82.81	93.04	4
Electricity	33	87.59	97.99	99.57	99.87	2
Print circuit board	25	1.38	50.02	77.46	90.23	4

[a] Match sector corresponds to the Taiwan IO table of 52 sectors, Appendix A in Electronic Supplementary Material

database. Moreover, the IO data were gathered from the Taiwan Environment Data Warehouse, the National Greenhouse Gas Emissions Inventory, the Accounting and Statistics of Taiwan IO table, and the Energy Balance Sheet of Taiwan. The 1-m^2 print circuit board was selected as a functional unit to compare the difference and uncertainty by the depth of the process inventory.

For the hybrid model, we can distinguish the connected tier between the process and IO matrix, up to the tier that is calculated by the process inventory, whereas anything beyond the tier belongs to the IO. Table 1 shows the IO inventory result of the PCB tier 1 supply chain; the IO inventory table was calculated from tiers 1 to 4. There were 16 components in the printed circuit board tier 1 supply chain. Each component can be assigned a sector category. The component emissions rate in each tier can be calculated by Eq. (1), (2), (3), and (4). The threshold M was set to 70 in the case study, which means that the process inventory makes over 70 % of the total emissions and that the IO inventory makes the remaining 30 %. The PCB's match sector here is sector 25. According to the IO inventory results of sector 25, the PCB tier 1 components produce 1.38 % of the emissions. Because the setting of the process inventory should include 70 % of the emission for each component, the inventory depth K_i^n should be higher than 68.62 %. Each component inventory depth would be different depending on the characteristics of the match sector. For example, the inventory depth is suggested to be tier 3 for copper and tier 2 for dipropylene glycol monomethyl ether.

Table 2 shows the results of the inventory analysis computed by integrated hybrid method from tier 1 to tier 4 and includes the improvement by the proposed M% threshold method. In the case of the printed circuit board, tier 4 is the most complete system boundary; we assume that the emissions are 100 % for benchmarking purposes. Comparing the five different process inventory results, "M% threshold improvement" which used the proposed method made 93 % of the emissions while tier 3 made only 54 %. For the hybrid

Table 2 Hybrid emissions by different tiers of the process inventory

Process inventory depth	Process (kg)	IO (kg)	Integrated hybrid (kg)	Process (%)	IO (%)	Integrated hybrid (%)
Tier 1	0.39	0.61	1.00	11.17	42.84	20.24
Tier 2	1.10	1.12	2.22	31.16	79.49	44.99
Tier 3	1.91	1.23	3.14	54.22	86.97	63.59
Tier 4	3.53	1.41	4.94	100.00	100.00	100.00
M% threshold improvement	3.28	1.27	4.55	92.97	89.56	91.99

model compilation result, tier 3 made only 64 %, while the "*M*% threshold improvement" rose to 92 % of the total emissions. The major difference comes from the components with significant emissions in tier 3 or 4, especially copper and glass fiber-reinforced plastic. These results show that the method can keep the most important emissions part in the process inventory and thus helps to reduce the cutoff uncertainty.

3.2 Discussion

In this case study, the Ecoinvent database was used for the purpose of illustration. It should be noted that the proposed method intends to identify where to collect new primary data rather than secondary data for a system because secondary data available from a database may not be superior to IO data. While the case study demonstrates that the proposed incorporation of the criteria into the integrated hybrid LCA helps improve the cutoff uncertainty, the PXC method also provides an efficient way to determine which process inventory should be utilized. The major difference between the proposed method and the PXC method lies in the proposed method's explicit evaluation of the significance of the process inventory that should be included. PXC uses SPA to rank the most important paths of environmental emission in the hybrid model, and process data are subsequently required for a number of top hot-spots of the paths (Acquaye et al. 2011). In contrast, this study identifies the tier for each sector where the process inventory is connected to the IO inventory based on an explicit cutoff value *M*%.

To determine the threshold *M*, the managers and practitioners would need to consider explicitly the cost and benefit of different types of inventory data. While this issue has not been explored sufficiently in this study, it is suggested that a framework of value of information could be developed to estimate the value of adding process inventory, which can be weighed against the cost of the process inventory analysis. As a first approximation, it has been estimated that for process-based LCA, the air emission is lower than EIO-LCA inventory by around 30–50 % under the same system boundary (Junnila 2006; Majeau-Bettez et al. 2011). If it is desirable for the integrated hybrid inventory to include 80 % significant emission (WRI and WBCSD 2011), the process inventory part would set the *M*% value at least 40–56 %. Further investigation is needed because the determination of *M* depends on sector characteristics and impact categories and will be influenced by the cost of inventory analysis.

The IO inventory evaluation varies according to the settings of the IO table. For the hybrid model, the number of sectors for the IO table can also influence the calculation result. The increase of the IO table sectors in the hybrid model has several advantages. One advantage is the reduction of the IO inventory uncertainty. Second, the efforts spent on process inventory can be saved because the IO inventory can play a more important role than the process inventory. Despite the advantages of strengthening IO inventory, uncertainty remains. First, because the calculation of multipliers of physical quantities uses a monetary input–output table, the physical flow of commodities may be distorted by the monetary value of the interindustrial transactions. Second, as the product supply chain goes beyond the IO table system boundary, the evaluation error arises because of the different industrial structures or the underestimation of the emissions in the transport stage. This trend occurs because the system boundary in the IO table is usually set for a country or a unique region. Third, the tiers of a process LCA database may not line up with the tiers of an IO database. Further study is needed to explore the way of harmonization of tiers between the two databases.

4 Conclusions

This study provides a clearer guideline for process and IO inventory cutoff criteria for upstream scope 3 emission inventory, which could help to address truncation uncertainty in the integrated hybrid LCA. Compared to other hybrid models, the integrated hybrid model is the newest and will be continuously improved. The determination of *M* value deserves further study under a framework of value of information. The cost of inventory analysis and the benefit of incorporating process inventory for the purpose of an assessment work need to be evaluated explicitly. When high-precision data were required, process LCI would play an important role, and a higher *M* value should be set. In this situation, the emissions from IO-LCI would be lower than for process LCI. However, precision itself is not the goal of the product inventory analysis; a lower *M* value might be appropriate if the analysis of the value of information provided justification.

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References

Acquaye AA, Wiedmann T, Feng K, Crawford RH, Barrett J, Kuylenstierna J, Duffy AP, Koh SCL, McQueen-Mason S (2011) Identification of 'carbon hot-spots' and quantification of GHG intensities in the biodiesel supply chain using hybrid LCA and structural path analysis. Environ Sci Technol 45(6):2471–2478

Andrae A, Andersen O (2010) Life cycle assessments of consumer electronics—are they consistent? Int J Life Cycle Assess 15(8):827–836

Baboulet O, Lenzen M (2010) Evaluating the environmental performance of a university. J Cleaner Prod 18(12):1134–1141

WRI and WBCSD (2011) Corporate value chain (scope 3) accounting and reporting standard—supplement to the GHG Protocol Corporate Accounting and Reporting Standard, USA

Hendrickson C, Horvath A, Joshi S, Lave L (1998) Peer reviewed: economic input–output models for environmental life-cycle assessment. Environ Sci Technol 32(7):184A–191A

Huang YA, Weber CL, Matthews HS (2009) Categorization of Scope 3 emissions for streamlined enterprise carbon footprinting. Environ Sci Technol 43(22):8509–8515

Junnila SI (2006) Empirical comparison of process and economic input-output life cycle assessment in service industries. Environ Sci Technol 40(22):7070–7076

Lave LB, Cobas-Flores E, Hendrickson CT, McMichael FC (1995) Using input-output analysis to estimate economy-wide discharges. Environ Sci Technol 29(9):420A–426A

Lenzen M (2000) Errors in conventional and input-output–based life-cycle inventories. J Ind Ecol 4(4):127–148

Lenzen M (2007) Structural path analysis of ecosystem networks. Ecol Model 200(3–4):334–342

Lenzen M, Crawford R (2009) The path exchange method for hybrid LCA. Environ Sci Technol 43(21):8251–8256

Majeau-Bettez G, Strømman AH, Hertwich EG (2011) Evaluation of process- and input–output-based life cycle inventory data with regard to truncation and aggregation issues. Environ Sci Technol 45(23):10170–10177

Matthews HS, Hendrickson CT, Weber CL (2008) The importance of carbon footprint estimation boundaries. Environ Sci Technol 42 (16):5839–5842

Rowley H, Lundie S, Peters G (2009) A hybrid life cycle assessment model for comparison with conventional methodologies in Australia. Int J Life Cycle Assess 14(6):508–516

Sinden G (2009) The contribution of PAS 2050 to the evolution of international greenhouse gas emission standards. Int J Life Cycle Assess 14(3):195–203

Suh S (2004) Functions, commodities and environmental impacts in an ecological-economic model. Ecol Econ 48(4):451–467

Suh S (2006) Reply: Downstream cut-offs in integrated hybrid life-cycle assessment. Ecol Econ 59(1):7–12

Suh S, Huppes G (2005) Methods for life cycle inventory of a product. J Cleaner Prod 13(7):687–697

Suh S, Kagawa S (2005) Industrial ecology and input-output economics: an introduction. Econ Syst Res 17(4):349–364

Suh S, Lenzen M, Treloar GJ, Hondo H, Horvath A, Huppes G, Jolliet O, Klann U, Krewitt W, Moriguchi Y, Munksgaard J, Norris G (2003) System boundary selection in life-cycle inventories using hybrid approaches. Environ Sci Technol 38(3):657–664

Treloar GJ (1997) Extracting embodied energy paths from input–output tables: towards an input–output-based hybrid energy analysis method. Econ Syst Res 9(4):375–391

Treloar GJ, Love PED, Faniran OO, Iyer-Raniga U (2000) A hybrid life cycle assessment method for construction. Constr Manag Econ 18(1):5–9

Williams ED, Weber CL, Hawkins TR (2009) Hybrid framework for managing uncertainty in life cycle inventories. J Ind Ecol 13 (6):928–944